Effect of Fragmentation Models on Atmospheric Energy Deposition

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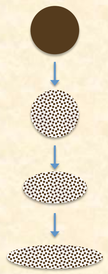
OBJECTIVE & APPROACH

The ultimate goal of our work is to understand the risk posed by asteroids with uncertain entry and strength parameters. During atmospheric entry, bolides deposit energy as they fragment, ablate, and are subjected to drag forces. Simplified fragmentation modeling approaches found in existing literature predict different energy deposition curves and resulting blast footprints. We compare four models to assess their fidelity, sensitivities to entry and strength parameters, and effects on blast wave risk estimates. We modeled energy deposition as a function of altitude, compared results against the Chelyabinsk meteoroid case and a high-fidelity simulation, and used a blast wave propagation model to compute resulting ground damage footprints. While the physics of asteroid trajectory, ablation, and fragmentation are important, extracting the key features and sensitivities of the entry process into simpler simulations is vital to producing an effective risk model.

MODELS

Liquid Drop/"Pancake"
(Hills & Goda, 1993)



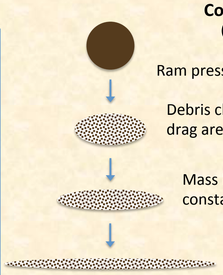
Ram pressure exceeds bolide strength.

Debris cloud forms.

Bolide mass "pancakes" from increased drag.

Mass continues to flatten under common bow shock until end of flight.

Collective Wake
(Revelle, 2005)



Ram pressure exceeds bolide strength.

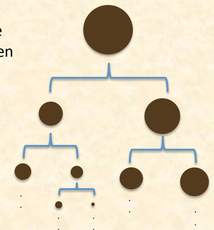
Debris cloud forms with twice the previous drag area and increased strength.

Mass breaks again. Effective mass remains constant while area doubles.

Process continues to ground, always under common bow shock.

Progressive Fragmentation – Non-Collective Wake
(Mehta et al., PDC 2015)

Ram pressure exceeds bolide strength. Bolide breaks into two children of nearly equal mass.



Children have greater strength, but continue to fragment as ram pressure increases.

Process continues to ground. Bolide pieces eventually cease fragmentation and may slow to terminal velocity.

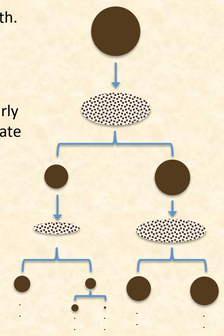
Combination Model – Progressive Fragmentation with "Pancaking"

Ram pressure exceeds bolide strength. Debris cloud forms and "pancakes" under a common bow shock.

Cloud reaches a critical radius and separates into two fragments of nearly equal mass. Fragments obtain separate bow shocks and are then treated independently.

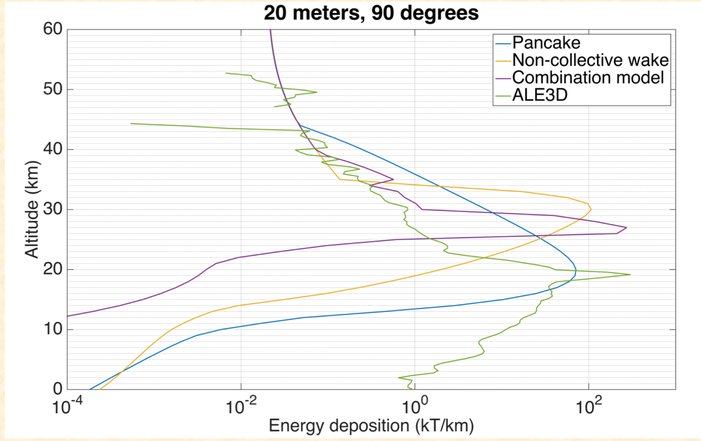
Pressure exceeds increased fragment strengths again, forming additional debris clouds.

Process continues to ground. Pieces eventually cease fragmentation and may slow to terminal velocity.

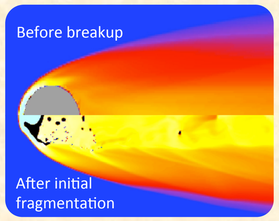


ALE3D MODEL COMPARISON

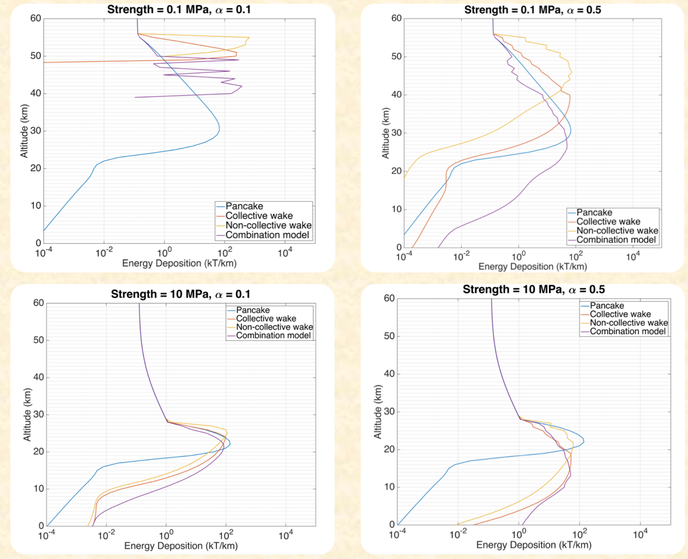
See poster by Darrel K. Robertson for more information on ALE3D



- ALE3D code enables high-fidelity, physics-based simulation of asteroid entry and breakup. Bolide is allowed to both pancake and fragment as dictated by the model physics.
- Burst altitude matches well with the pancake model, though the combination model agrees more closely with energy deposition during initial onset of fragmentation.
- Curve tail is not approximated by any of the compared models, though this may be due to a mesh resolution issue in ALE3D.
- Depending on the intended application, a simplistic model appears to be capable of capturing key features (such as burst height and value of energy deposition peak).



SENSITIVITY TO STRENGTH PARAMETERS



- Strength = Ram pressure at break point → $\sigma = \rho_{air} v^2$.
- $v = f(\rho_{air})$ so strength can be prescribed based on desired break altitude.
- α varies with the pre-cracked nature of the asteroid's internal structure, though the fracture pattern may change as the bolide fragments.
- Assuming constant α, a higher value results in fewer and more pronounced fragmentations.
- Shows limitation of pancake model in allowing for existing structure of bolide.

VALIDATION TEST - CHELYABINSK

Test Case Parameters:
- d = 19.8 m
- v = 19.16 km/s
- θ = 18.3°
- ρ = 3.30 g/cc

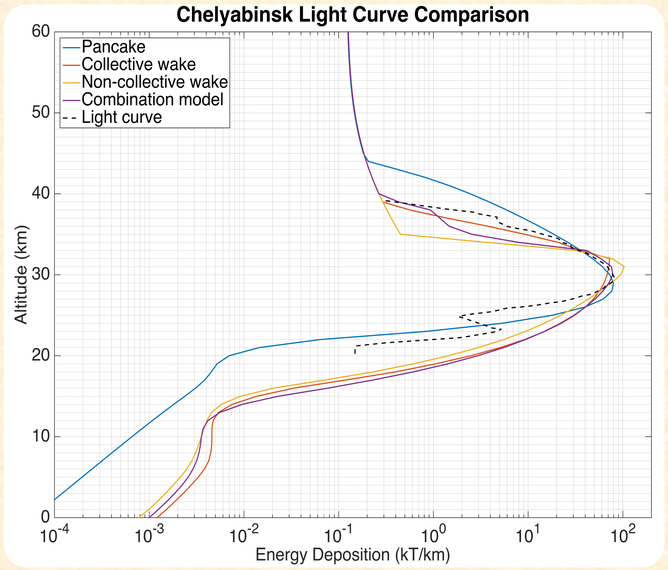
Fragment strengths scale as:

$$\sigma_c = \sigma_p \left(\frac{m_p}{m_c}\right)^{\alpha}$$

where p = parent, c = child, α = Weibull scaling exponent.

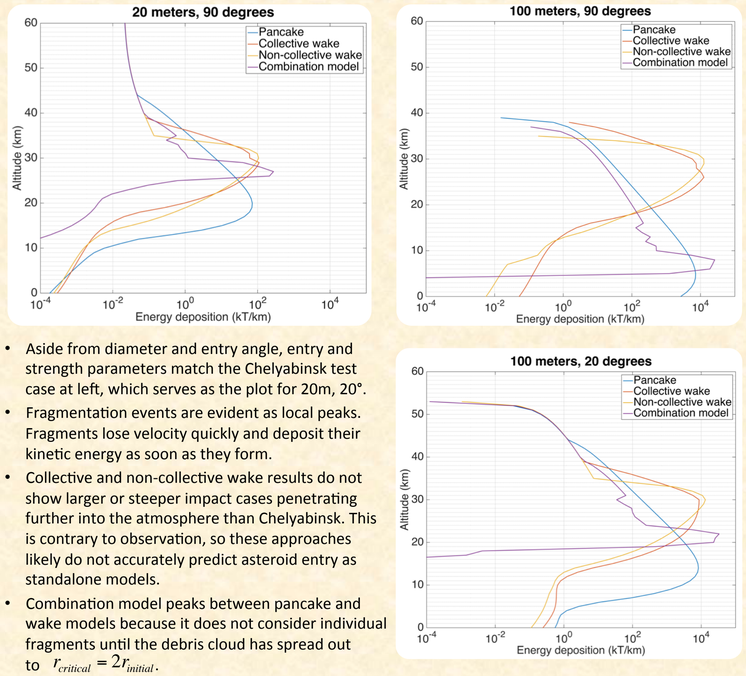
α and initial ρ tuned to match observed light curve:

- Pancake
  - Strength = 0.7 MPa
  - α = (not part of model)
- Collective Wake
  - Strength = 1.8 MPa
  - α = 0.2
- Progressive Fragmentation
  - Strength = 3.5 MPa
  - α = 0.15
- Combination Model
  - Strength = 1.5 MPa
  - α = 0.15



- Initial strength and α depend on pre-entry fracture conditions and are difficult to determine with the current lack of data.

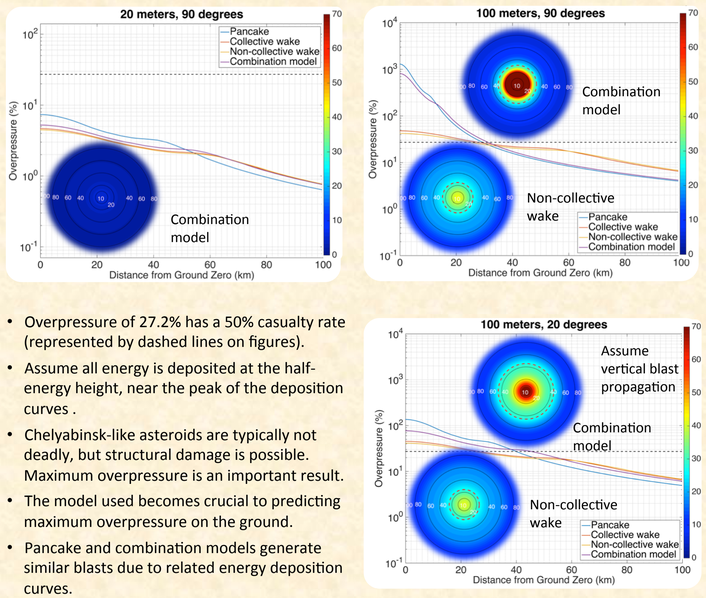
SENSITIVITY TO ENTRY PARAMETERS



- Aside from diameter and entry angle, entry and strength parameters match the Chelyabinsk test case at left, which serves as the plot for 20m, 20°.
- Fragmentation events are evident as local peaks. Fragments lose velocity quickly and deposit their kinetic energy as soon as they form.
- Collective and non-collective wake results do not show larger or steeper impact cases penetrating further into the atmosphere than Chelyabinsk. This is contrary to observation, so these approaches likely do not accurately predict asteroid entry as standalone models.
- Combination model peaks between pancake and wake models because it does not consider individual fragments until the debris cloud has spread out to $r_{critical} = 2r_{initial}$.
- Typical initial dispersion velocities are 100 m/s (derived from ratio of air density to mass density).

BLAST WAVE FOOTPRINT

Blast wave code provided by Scott L. Lawrence



- Overpressure of 27.2% has a 50% casualty rate (represented by dashed lines on figures).
- Assume all energy is deposited at the half-energy height, near the peak of the deposition curves .
- Chelyabinsk-like asteroids are typically not deadly, but structural damage is possible. Maximum overpressure is an important result.
- The model used becomes crucial to predicting maximum overpressure on the ground.
- Pancake and combination models generate similar blasts due to related energy deposition curves.
- The two wake models produce similar results to each other as well.

CONCLUSIONS & FUTURE WORK

Although they are at opposite extremes in terms of complexity, the pancake and combination models produce similar curves in all of the above studies and seem to describe the airburst process more intuitively than other existing models. Used in tandem, these two models can roughly outline the energy deposition and relevant features of the asteroid entry process. Future work includes refining both asteroid breakup and blast wave models, as well as simulating additional observed impact events.

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